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AUTHOR(S) Stirling A. Colgate, T-6

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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COSMIC RAYS, SUPERNOVA, AND THE ORIGIN OF ULTRAHIGH ENERGY PARTICLES

S. A. Colgate
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Prologue

At this conference in honor of Al Cameron - organized by his many and able students - it was remarked how all the organizers, Al's students, avoided giving talks and writing papers such as this. However, the perfect topology was broken because unaware to them, I have considered myself in the same category as one of Al's students. My education in astrophysics started a bit later in age than the organizers, but Al was no less rigorous. I remember him asking me such student-oriented questions as:

1) What nuclear synthesis would happen behind such supernova shocks?

2) How would you get enough light out of a supernova to make a quasar?

3) How could you power a quasar with supernova?

4) What prompt gamma rays and x-rays would you get from a supernova?

Once I had finished a few of these assignments, I was both a student of Al's and an astrophysicist

Abstract

The acceleration of ultrahigh energy cosmic rays, $\gtrsim 10^{15-20}$ eV, is still an unsolved problem in high-energy astrophysics. The now classical mechanism of stochastic acceleration of cosmic rays in a strong shock in the interstellar or intergalactic medium is limited in time and dimension for all likely acceleration sites, particularly for

the highest energies. Acceleration of cosmic rays across a plasma shock of velocity, β_s ($\beta_s = v_{shock}/c$), requires $1/\beta_s$ number of crossings ano therefore $(1/\beta_s)^2$ number of scatterings for doubling the energy of a particle. This requires a space of the order of $1/\beta_s \times$ the scattering length, or a multiple of the Larmor radius and hence, the space requirements for cosmic ray acceleration are very many Larmor orbits in dimension, as well as times that are larger by $(1/\beta_s)^2 \times t_{Larmor}$. The acceleration of cosmic rays by the shock in the envelope of a Type I supernova is reviewed, and the interaction of the accelerated matter with the nearby ISM is considered. The spectrum of relativistic ejected matter is preferentially trapped in the ISM. Further acceleration of each energy group should take place in both the near relativistic shock wave and the compression by the following matter. The possible acceleration of ultrahigh energy cosmic rays in the accretion disk of a near-stationery magnetic neutron star such as Cyg-X3 is another strong possibility. Here the diffusion of magnetic flux radially outwards opposite to the viscous diffusion of mass radially inwards is considered as a likely topology for a unipolar generator acceleration of ultrahigh energy particles.

Introduction

The highest thermal temperature observed in astrophysical phenomena is probably the gamma burst associated with the March 5th event where $kT \cong 20$ keV. The highest nonthermal phenomena is certainly the ultrahigh energy cosmic ray spectrum extending up to $\sim 10^{20}$ eV. The highest energies are the most difficult to explain. In Fig. 1 from Hillas (1984), the distribution of cosmic ray energy as a function of flux is shown as a band describing the limits of error from the lowest energy to

10^{20} eV or $\Gamma \equiv \sqrt{1-\beta^2} = 10^{11}$. The high energy region, above 10^{19} eV, shows several possible modifications from the original curve. In particular the partially conflicting results from the Yakutsk group (Atrashkevich et al. 1985), and recent Fly's Eye (Baltrusaitis et al. 1985) experiments are compared to the extensive data from Haverah Park. In addition the spectrum expected from progressive black body photon attenuation (Stecker 1968, Schramm and Hill 1983), is shown as would be expected if the cosmic rays are stored in the metagalaxy and attenuated by rays by interaction with the black body photons. This produces a modest peak and then a sequentially reduced or steeper spectrum as a function of age. Recently the Fly's Eye experiment seems to confirm the more rapid fall-off with energy previously indicated by the Yakutsk data, so that presently there is some uncertainty concerning the ultra-high energy spectrum, i.e., whether it is flat, or falls off as expected due to the black body radiation. If indeed the more extensive Fly's Eye data confirm the roll off of the spectrum in the neighborhood of 10^{20} eV, as expected from interaction with the black body radiation, then we will begin to have a consistent picture of the highest energy cosmic rays interacting in the metagalaxy with the primordial photons. This in turn is only partially consistent with the measurements of anisotropy as a function of energy, Fig. 2, that shows relatively large anisotropy at the very highest energies consistent with galactic as well as extra-galactic sources. On the other hand there is another reason to expect an upper limit of 10^{20} eV, namely the Cyg X-3 machine.

Some Mechanisms of Astronomical Acceleration

The one characteristic of astronomical accelerators compared to human accelerators is the high probability of particle loss as a function of acceleration. This frequently leads to power law spectra.

A few of the mechanisms that have been considered to produce high energy particles are:

(1) The Fermi mechanism in the interstellar medium depends upon stochastic particle interaction with turbulent clouds. In a sense this process is a thermalization of the low-mass particles, cosmic rays with the super-massive particles, and magnetic clouds. A problem is the likelihood of charged-dependent acceleration. The fact that the cosmic ray spectrum is highly independent of the charge of the various nuclei has led to the consideration of other mechanisms.

(2) By far the most popular explanation of intermediate energy cosmic rays is the plasma shock in the interstellar medium from the bulk motion of supernova ejecta (Bell 1978, Axford et al. 1977, Blandford and Ostriker 1978, Krymsky 1977). A finite compression across the shock is stochastically sampled by cosmic-ray particles diffusing back and forth across it. This stochasticity and the attendant probability distribution of loss leads to a power-law spectra very close to what is observed. However, as LaGarge and Caesarsky (1983) have shown, the maximum likely energy to be achieved by a shock wave in the interstellar medium is only 10^{13-14} eV. This limit is determined by the finite time and dimension (magnetic flux) in the region of the supernova shock wave before it decays.

(3) A third mechanism is the hydrodynamic shock in the envelope of a compact supernova, presumably a Type I supernova (Colgate and Johnson 1960, Johnson and McKee 1971, McKee and Colgate 1973, Colgate and Petschek 1979, and Colgate 1984). This mechanism, in contrast to the previous two, is not stochastic in the usual sense, but instead depends

upon a purely hydrodynamic property of a shock wave progressing and strengthening in the density gradient of a stellar supernova envelope. A shock wave initially formed from a thermonuclear explosion, or a standing shock on a collapsing neutron star core, experiences some 14 orders of magnitude change in density, and a somewhat larger change in mass fraction before reaching the surface layer of the supernova envelope. It is these very large orders of magnitude that allow the possibility of the hydrodynamic origin of cosmic rays. However, current analytical and numerical modeling would indicate a power law spectrum too steep by one power of E to agree with observations. In addition the escape of cosmic rays after interaction with the nearby interstellar medium is problematic. There exists the possibility that the energy may be either drastically decreased or increased by this interaction.

(4) A rotating magnetic neutron star allows the possibility of acceleration at the singularity at the light cylinder of a corotating magnetic field (Berenzinsky 1983). The stress of a near-relativistic velocity plasma at the light cylinder modifies the field geometry in a way that is still not agreed upon. The accumulation of mass at the singularity tends to break the topology such that acceleration to extremely high energies would seem unlikely unless a highly contrived distribution of plasma flow is arranged.

(5) A pulsar rotating off axis will excite Alfvén waves (Gunn and Ostriker 1969), which in turn give rise to strong wave-particle in-phase acceleration, and very high cosmic ray energies. This phenomena, unfortunately, is sensitive to a phase destruction due to plasma loading of the waves (Kegel 1971). Strong Alfvén waves from an off-axis pulsar may be seen in the Crab Nebula. The preservation of the phase relation-

ship necessary for ultrahigh energy particle acceleration is still uncertain.

(6) Reconnection in helical, force-free magnetic fields of the form, $\vec{B}_\theta + \vec{B}_z$, leads to acceleration by the parallel electric field, $E_{||}$, due to the interruption of the $J_{||}$ current. An acceleration parallel to B is attractive because at the very highest energies, 10^{20} eV, synchrotron radiation even by protons is immense. For example, a 10^{20} eV proton will radiate its own energy in a pulsar magnetic field of 10^{12} gauss within a distance of a fraction of a micron. Hence $\vec{E}\cdot\vec{B}$ acceleration is attractive for 10^{20} eV particles whenever magnetic fields are stronger than a few gauss. The problem with reconnection, or namely the enhanced resistivity produced in force free field configurations, is that there is only now emerging a concensus in plasma physics of how it occurs. The creation of the turbulence necessary for reconnection is probably best described as being driven by an anisotropic velocity distribution (Meyerhofer and Perkins 1984). Probably the most complex physical phenomena that has ever been understood is the plasma loss from a Tokamak fusion toroidal confinement experiment. Perhaps the understanding of this turbulence-driven reconnection phenomena will be applied throughout astrophysics, but currently it is too complex and too uncertain to base a theory of the origin of the ultra-energetic particles with confidence. On the other hand there is no confidence in any other mechanism for that matter.

(7) An emerging possibility for the acceleration of cosmic rays in this galaxy, as well as all others, is the possibility that the Cyg X-3 machine is universal. Here the startlingly high energy gamma rays believed to have been observed from this binary star x-ray source of

greater than 10^{15} eV (as well as several other sources) implies an accelerator of (probably) protons of 10^{15} to 10^{17} eV. There is suggestion by Chanmugan and Brecher (1985) that this accelerator is similar to the accretion disks postulated for black holes and quasars (Lovelace 1976, Blandford and Vnajek 1977). I would like to suggest, at the end of this paper, that a more likely explanation resides in understanding the unipolar generator associated with a near-stationery magnetized neutron star and an accretion disk. The one major problem with any acceleration mechanism near a neutron star is finding a rational explanation for the effective electrical insulation.

The general property of all these mechanisms with the possible exception of the supernova envelope shock, is that a time-dependent loss during a time-dependent acceleration leads to a power law distribution of accelerated particles.

Stochastic Shock Acceleration

We discuss next the stochastic shock acceleration in the interstellar medium with the purpose of extending this discussion to the very difficult problem of finding a possible site for such shock acceleration of ultrahigh energy particles in the intergalactic environment. This discussion follows mostly that of Hillas (1984). The fundamental assumption of a cosmic ray acceleration shock is that the major fraction of the energy density of the shock remains local, and does not diffuse to places where the conditions of the medium are significantly different, i.e., the local Hugoniot relations apply. One generally assumes a parallel shock, that is where B is roughly parallel to the direction of shock propagation because this represents the majority circumstance in terms of solid angle. A very small departure from a perpendicular shock allows relativistic particles to escape along lines of force. We further assume that the shock velocity is small or $\beta_s << 1$. The energy gained by a particle crossing such a strong shock is of the order of $E\beta_s$, and the particle loss by convection downstream is determined by the number of crossings $\cong 1/\beta_s$. Particles are lost when they are convected downstream at the fluid velocity $\cong 1/4\ \beta_s$. Then analogous to photon diffusion, this occurs at an "optical depth" $\tau = 1/\beta_s$ from the front. On the average $\tau^2 = (1/\beta_s)^2$ scatterings will take place before the particle will get lost downstream during which time a particle will cross the shock front $\tau = 1/\beta_s$ times roughly doubling its energy. Therefore there are two requirements: space $\gtrsim (1/\beta_s)$ scattering lengths and time $\gtrsim (1/\beta_s)^2$ scattering time.

These results when combined with statistics result in a spectrum $dN/dE \cong E^{-2}$ and hence the cosmic ray spectrum. This requires that particles be scattered on either side of the shock as shown in Fig. 3. There will be two different mean free paths, upstream and downstream, λ_1 and λ_2. Typically the shock speed is 10^8 cm s^{-1}, or $\beta_s = 1/300$, and therefore 4×10^5 scatterings are required for ten-fold energy gain. It is this very large number of scatterings that requires that no other phenomena interfere. In particular, energy lost by ultrahigh energy particles is suggested by Eichler (1984). This requires a very delicate balance between gain and loss at high energy, so as not to alter the Hugoniot relations based on the local assumption. The rate of energy gain from such a shock is then $\cong c\beta_s^2/(\lambda_1+4\lambda_2)$ as given by LaGage and Cesarsky (1983).

The scattering either side of the shock must depend on Alfvén wave turbulence, which in turn must be excited by an anisotropic distribution of the upstream flux of particles. A reasonable estimate of the distance required to scatter a particle in non-saturated Alfvén wave turbulence is $\lambda_1 \cong 10R_{Larmor}$. This assumes a distribution from saturation turbulence at the shock from to negligible turbulence in the ISM. The growth rate of the relevant velocity space instability is energy density and isotropy dependent. Then the space or distance ahead of the shock required for acceleration is $L = \lambda_1/\beta_s$ or $3 \times 10^3\ R_{Larmor}$. A supernova collides with roughly a thousand times its mass in 30 to 50 parsecs radius, and hence this is the radius of what might be called the strong shock in the ISM where $\beta_s = 3 \times 10^{-3}$. For an energy gain of tenfold for each particle, the limiting energy corresponding to this radius, or 3×10^3 Larmor radii, is 3×10^{13} eV. Hence this is upper energy limit for supernova shock acceleration in the ISM. By way of comparison, a 10^{20} eV proton has a Larmor radius of 30 kpc in a 3 μg field or roughly one galaxy diameter. An extension of these same arguments restricts the possibility of reaching the energy of ultrahigh energy cosmic rays in any known extragalactic sites.

Sites for Possible Extragalactic Ultrahigh Energy Cosmic Ray Acceleration

Consider a typical shock strength of $\beta_s = 1/300$ and a required acceleration dimension of 3000 Larmor radii. For a typical extragalactic magnetic field of 10^{-8} gauss, this requires a dimension of 3×10^4 Mpc, a dimension greater than the size of the universe. Even a relativistic shock requires a dimension of 100 Mpc, but such a shock would be highly luminous in a region larger than the local supercluster to say nothing of requiring an energy density at least 10^7 times the typical ambient medium energy density of 100 eV. Radio galactic lobes of typical dimension several times 10 kpc and possibly several microgauss average field are no better than our own galaxy, which is inadequate by 10 to 10^3, depending upon the shock strength. The hot spots within these lobes, radio galactic hot spots, may be 1/10 the lobe dimension and times 10 the magnetic field strength. This is still inadequate in size and field unless the shocks are relativistic and the accelerated particles high Z like iron nuclei. The frequent occurrence of both these circumstances seems unlikely as discussed by Hillas (1984). Recently Jokipii and Morfill (1985) have suggested acceleration in the galactic wind shock at $R_{galactic} = 100$ kpc, $\beta_s = 1.7 \times 10^{-3}$ and $B_{wind} = 1.8 \times 10^{-7}$ gauss. Even assuming an Archimedes' spiral field, Bohm diffusion, i.e., λ_s = Larmor radius, the space is too small by 3.6×10^3 for a 10^{20} eV proton. The alternative suggested by Jokipii (1985) is to assume a perpendicular shock.

Time of Acceleration

In addition, the field strength must not be too great, otherwise synchrotron radiation becomes too large, and the particles are decelerated by radiation emission in a time shorter than required for acceleration. The time for emission of the kinetic energy of a 10^{20} eV proton by synchrotron radiation is $t_s = 1.4/(E_{20}B^2)$ years. Consequently, a typical presumed quasar magnetic field of 100 gauss is too large, and if we let $R_{Lamor}/c = t_s$, $B \leq 4/E_{20}$ gauss. This excludes many other possible sites for acceleration unless the acceleration is parallel to B.

Active Galactic Nuclei Photon Losses

There has been frequent reference (Brecher and Burbidge 1972) to possible acceleration of ultrahigh energy particles in active galactic nuclei, quasars, etc. There is one major problem with acceleration in active galactic nuclei (AGN) and that is, if a particle is accelerated from within such an such an object, it must encounter a fraction of the photons by which we observe it. A large energy density of photons is implied by the short fluctuation times and large luminosities observed. A proton of 10^{20} eV, interacting with such an optical or infrared photon, is transformed by its energy factor, $2\Gamma \cong 10^{11}$, to a photon whose energy is sufficient $\gtrsim 10^{11}$ eV, necessary to radiate π's as well as a zoo of other particles. The energy loss becomes immense even for Compton scattering, and meson interactions will increase this by several orders of magnitude. A 10^{20} eV proton traversing the radiation field of the quasar 3C273, causes the proton to radiate by Compton scattering alone some thousand times its kinetic energy, and hence a small fraction of the traversal of such an object in any proposed acceleration process would cause a radiation damping that far exceeds any plausible acceleration (Colgate 1984). The infrared emission is much worse than the optical because of the higher photon energy density and the still greater photon number density. X-ray sources that have shorter fluctuation times imply smaller sizes and comparable or even greater photon energy densities, and hence are even more unlikely to produce ultrahigh energy particles without overwhelming radiation loss. As a general rule, if we can observe any object by radiation outside the radio spectrum, its photon density will be so great as to prohibit the acceleration of ultrahigh energy particles.

Supernova Envelope Shock

If the supernova envelope shock propagates into a tenuous magnetosphere of the presupernova star, it could create ultrahigh energy particles and avoid the problem of radiation and finite Larmor orbit. In this case acceleration occurs in the bulk matter by a pressure gradient in the local comoving frame of the relativistically ejected matter. A strong relativistic shock similar to a nonrelativistic shock divides energy equally between kinetic and internal energy density. The mass density of this internal energy density means that the fluid velocity, and hence kinetic energy per original particle, is initially relatively small. The subsequent expansion (and acceleration) results in a final energy of expanded relativistic matter that far exceeds the initial kinetic energy of the same matter immediately behind a relativistic shock. This acceleration is then relatively free of the constraints of Larmor radius and dimension.

A relativistic SN envelope shock requires a small compact white dwarf as a presupernova star where the surface radius is $\cong 10^8$ cm. The central density is 10^9 to 10^{10} g/cm^{-3}, and the surface density is 10^{-4} g/cm^{-3}. The ratio is then $\rho_{cen}/\rho_{surf} \cong 10^{14}$ and the mass fraction of the surface is 10^{-16}. An explosion, either thermonuclear or neutron star collapse inside of this mass distribution will always lead to a strong shock because of high sound speed inside and a low sound speed outside. A nonrelativistic shock in a density gradient gives rise to $\varepsilon_{shock} \cong \rho v_f^2/2 \propto F^{-0.4}$. The external mass fraction $F \propto N(>E) \propto E^{-2.5}$. This applies to an envelope structure similar to a polytrope of index 3. Unfortunately this integral spectrum $E^{-2.5}$ is too steep to give a cosmic ray spectrum by roughly one power of E. There is, however, lots of energy from the supernova, so that the total energy with a relativistic factor $\Gamma > 2$, i.e., kinetic energy equals the rest mass, is $c^2 F_{(\Gamma = 2)} M_\odot/2 \cong 5 \times 10^{48}$ ergs for $F_{\Gamma=2} = 10^{-6}$. One needs roughly double this or

10^{49} ergs for Type I supernova to maintain the cosmic rays in the galaxy.

Relativistic Shocks

A plane parallel relativistic shock gives rise to an energy vs mass fraction $E \propto F^{-.48}$ or, $N(>E) \propto E^{-2}$ and for a spherical shock wave possibly $\propto E^{-2.5}$. The maximum energy when such a shock wave breaks through the stellar surface layer ($\rho r \cong 1$ g cm^{-2}) is of the order $\Gamma \cong 10^5$ to 10^6, $\cong 10^{14-15}$ eV. This limit is similar to the stochastic shock acceleration within our galaxy, but in this case there are significantly fewer particles than are necessary for cosmic rays. The composition of such matter is determined by the original composition (presumably recently accreted) and the fact that immediately behind the shock the lepton density, i.e., from pairs, is roughly 10^4 per nucleon. These additional leptons supply the cushion for acceleration of the heavy nuclei in the shock transition so that heavy nuclei can be accelerated in the shocked fluid without decomposition due to nuclear spallation Hence the shocked material should carry the same composition as the unshocked material of the presupernova envelope, which in turn should correspond to the composition of the material recently accreted from the companion binary star. This mass fraction is so small, ($< 10^{-6}$) that it has not been altered by nuclear processes.

Fig. 4 shows the energy vs mass fraction expected from a shock in the envelope of a compact white dwarf for a SNI. By turning the graph 90° one obtains a cosmic ray spectrum where log F^{-1} becomes equivalent to log $N(>E)$ and log $(\Gamma-1)$ becomes the energy scale. In addition the density of a degenerate polytrope is superimposed along with the temperature behind the shock. One notes that in the relativistic region, the shock temperature is of the order of several 10^9 degrees, enough to cause some nuclear synthesis in the relatively short time before expansion. One also notes the relatively large difference between the energy of the shocked matter immediately post shock and the energy after expansion. This relatively large factor at high energies, for ultra-relativistic shocks, is due to the fact that the energy behind the shock resides in mass energy density. Upon expansion this mass energy density, photons and pairs, recombine and is converted into kinetic energy of a relatively few nucleons. Hence a relatively modest relativistic shock at the surface of the neutron star with an energy factor $\Gamma_s = 80$ corresponds to a post expansion energy factor of $\cong 10^6$. A nucleon is then accelerated in the comoving relativistic fluid frame by the pressure gradient associated with the original heat deposited by the relativistic shock. One notes in this figure the line drawn to indicate what would be required to produce the cosmic ray spectrum if no subsequent loss or gain mechanisms apply. One observes the relatively large difference between the observations and the expected spectrum. Various effects of interaction within the galaxy occur that may make this worse or better.

The High Energy Limit

When a shock breaks through the surface of such a supernova star, $\Gamma_s \cong 80$, the initial surface conditions will be scale height, $h_{surface} \simeq 100$ m, $\rho_{surface} = 10^{-2}$ g cm^{-3}, $h\rho = 1$ g cm^{-2}, $F \simeq 10^{-16}$. The relativistic shock, $\Gamma_s = 80$, will compress the fluid in the comoving frame by a factor of $4\ \Gamma_s$ to a nucleon density of 3 g/cm^3 and a rest mass density of 240 g/cm^3. It is this relativistic fluid with a few impedded nucleons that ultimately expands to a Γ of roughly 10^5 to 10^6 or

10^{14-15} eV per nucleon, depending upon the details of spherical expansion.

One next observes that if the local magnetic field were 10^6 gauss, a modest value for such a star, the flux within one scale height would be 10^8 gauss cm which is sufficient to contain a proton, local to the scale height, with $\Gamma_{fluid} = 80$. Hence a relatively modest imbedded magnetic field of a corona of such a star holds the possibility of propagating the relativistic shock to much lower densities and much higher energies. The limiting case corresponding to a final scale height of 5×10^3 cm and density 10^{-14} g/cm^{-3} and coronal density n_e of 10^{10} cm^{-3}. This corresponds to a coronal external mass fraction of 5×10^{-20} of the star or Γ_{final} of 10^{11-12} or an energy $E = 10^{20}$ eV. The relativistic shock in the magnetized plasma is dominated by the rest mass of its energy density, namely, pairs, photons, and a modest magnetic field. The Larmor radius of a proton is always small compared to the local scale height in the comoving frame. Hence ultrarelativistic acceleration is feasible in the expansion of such a relctivisitc fluid, but it has other major problems like running into the interstellar medium.

Expansion in ISM

The usual picture of the expansion of the mass ejected from the supernova is that it blows a "bubble" in the interstellar medium causing the matter internal to the bubble to undergo adiabatic expansion by PdV work (Kulsrud and Zweibel 1975). Figure 5 shows a picture of the expansion of such a bubble with cosmic rays presumably reflecting from the magnetic boundary back into the expanding debris. The reflection of such particles back into the expanding bubble takes place because of hydromagnetic waves or Alfvén wave scattering. This is the same scattering as is invoked for the return of particles back and forth across the shock in the stochastic shock acceleration mechanism. The excitation of such wave turbulence requires a progression of a relatively large anisotropic flux (energy density $\leq (B^2/8\pi)$) and a distance of $\cong$ 10 Larmor orbits before the necessary turbulence is excited, i.e., see LeGage and Cesarsky (1983) for an analysis of the gradient of hydromagnetic turbulence intensity ahead of the shock.

Relativistic Piston and Shock Interaction with the ISM

An alternate view of the supernova expansion into the ISM is that the relativistic ejected matter is trapped in the magnetic boundary and stochastically shock accelerated, Fig. 6. The energy density of the cosmic rays ejected from such a relativistic supernova shock first expands as a relativistic piston. The leading cosmic rays are of course the most energetic, but immediately following is a larger mass fraction of lower energy matter. The distribution in space of this distributed-in-energy piston is surprisingly compact. For example, the radius at which the relativistic cosmic rays, $\Gamma = 2$, collide with equal mass of the ISM, $n_{i,e} = 0.1\ \mathrm{cm}^{-3}$, is determined by:

$$M_{\Gamma=2}\ A = n_{i,e}\ R^3\ 4\pi/3 \quad .$$

where the mass of cosmic rays, $\Gamma>2$, is $FM_{\odot} = 10^{27}$ g. Then the radius of equal mass is $R = 2 \times 10^{17}$ cm. The linear separation will be; $\Delta R = R(1-\beta)$, and so since $(1-\beta) = \Gamma^{-2}/2$ cosmic rays of $\Gamma \cong 20$ will correspond to ΔR of $10^{-3}\ R = 2 \times 10^{14}$ cm. The distance necessary to excite hydromagnetic turbulence for scattering 10 Larmor radii is also 2×10^{14} cm for a proton of $\Gamma = 20$ in an ISM magnetic field of 3×10^{-6} gauss.

Hence the point where the interaction of the SN ejecta first becomes subrelativistic is close to where the dispersion in ejecta velocities first allows the excitation of the turbulence necessary to scatter the cosmic rays back into the expanding bubble. On the other hand the cosmic rays are now well embedded in the galactic magnetic field. In order to return to the vacuum bubble, the particles must scatter upstream in a near nonrelativistic medium where the flux of particles is greater by the ratio β^2c^2M/R^2. Since we are now concerned with a near relativistic piston driving a near-relativistic shock in the ISM, $v^2 \propto M^{-.4}$, then the flux is proportional to $M^{0.6}/R^2$. Therefore the hydromagnetic turbulence at any given time will be greater at smaller radii, and the cosmic rays will tend to be trapped ahead of a near relativistic shock. If cosmic rays are later accelerated at near zero energy in the ISM by a relatively weak shock of $\beta_s \cong 1/300$, then an initial relativistic distribution should be far more energized by a near relativistic shock operating on a particle distribution already near the desired final one. However, the effectiveness of the shock scales as (shock time/time for acceleration) = $(R/\beta_s)/\beta_s^2$ or $\beta_s R$, but the nonrelativistic shock velocity scales

$$\beta_s = (M^{0.6}/R^3)^{1/2} = M^{0.3}\ R^{-3/2}\quad .$$

Then the effectiveness scales as $M^{0.3}\ R^{-1/2}$ and since the radius where equal masses interact gives $M \propto R^3$, the final effectiveness of the shock acceleration scales as $R^{0.4}$ which weakly favors a large radius weak shock. The radius ratio favors large radii by the ratio $(R_{initial}/R_{final})^{.4}$ or a factor of 10. The relativistic shock spectrum is already seeded with particles up to at least 10^{14-15} eV, but weaker in number by roughly $E^{-0.8}$. The subsequent post-shock expansion is comparable for both regions of the supernova ISM shock.

The energy multiplication required for the supernova-injected spectrum is so much smaller than that starting from thermal in the ISM, that the injected spectrum and the ISM relativistic shock post-acceleration would seem to be more likely to produce the observed cosmic rays. Certainly the previously proposed large adiabatic expansion deceleration is unlikely and a post-relativistic ISM shock acceleration more likely, but the final outcome is not evident.

Cyg X-3 Cosmic Ray Acceleration

It has been well recognized that the ultrahigh energy gamma rays > 10^{15} eV and up to 10^{16} eV observed by Cyg X-3 are a strong indication of an extraordinary accelerator (Eichler and Vestrand 1984). The cascade models of gamma ray production from relativistic ultrahigh energy protons would indicate that the most likely source of the gamma rays comes from protons of roughly 10 to 100 times higher energy or a minimum of 10^{17} eV. Cyg X-3 is evidently a neutron star and a binary with an accretion disk, since this model fits the x-ray source. With this as the starting point, Eichler and Vestrand (1984) and now recently Chanmugam and Brecher (1985) have proposed models of the acceleration of particles in such an environment. These are either a rotating magnetized neutron star as Eichler (1984) considered, or as Chanmugam and Brecher (1985) considered, an accretion disk threaded with a magnetic field compressed and convected with the accreting mass flux. This model is essentially that proposed for quasars and active galactic nuclei by Lovelace (1976) and independently by Blandford (1976). I would like to consider a slightly different view of such an accelerator.

The magnetic field in the Chanmugam-Brecher (1985) model is presumed convected with the radial flowing mass flux of the accretion disk, as indeed it must be in the case of a black-hole accretion for an active galactic nuclei. The reason is that there is no central object in the case of a black hole to pin and support the magnetic flux necessary to thread the accretion disk to result in the high voltages required for acceleration. Instead, we consider a magnetized neutron star, essentially stationary, and allow an accretion disk surrounding it, Fig. 8. We point out that the magnetic flux of a neutron star should diffuse radially outward into the convectively evolving disk despite the opposite and implied radially inward mass flow. The magnetic flux in the neutron star should diffuse radially outward in a steady-state vacuum situation simply because the angular momentum of the disk must be flowing radially outwards by whatever diffusion mechamism is leading to the viscosity necessary for the radial accretion of the matter in the first place, namely, the α-viscosity of the disk. Presumably the diffusion that leads to the α-viscosity must allow diffusion of the vector field in both directions, so that a gradient of magnetic flux, steeper than the vacuum field configuration, should lead to a relaxed state of magnetic flux threading the disk. Under these circumstances, we have a field threading the disk much like a unipolar generator, Fig. 9. It is a simple matter to integrate the equations to give the electric field to obtain a total potential of 10^{20} eV. The catch 22 in this picture is that the electric field generated by the unipolar generator must exist along the lines of force between the disk and the neutron star. Just why such a large electric field should not lead to breakdown by pairs and gammas and then the current necessary to maintain the magnetic hydrodynamic conducting limit is a puzzle. However, the circumstance of a binary accretion disk and neutron star x-ray source, and a necessary α-viscosity, leads one to suspect that there is a pony somewheres. A conclusion is that there is as yet no conclusion to the problem of how to accelerate the ultrahigh energy cosmic rays.

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29J/sc

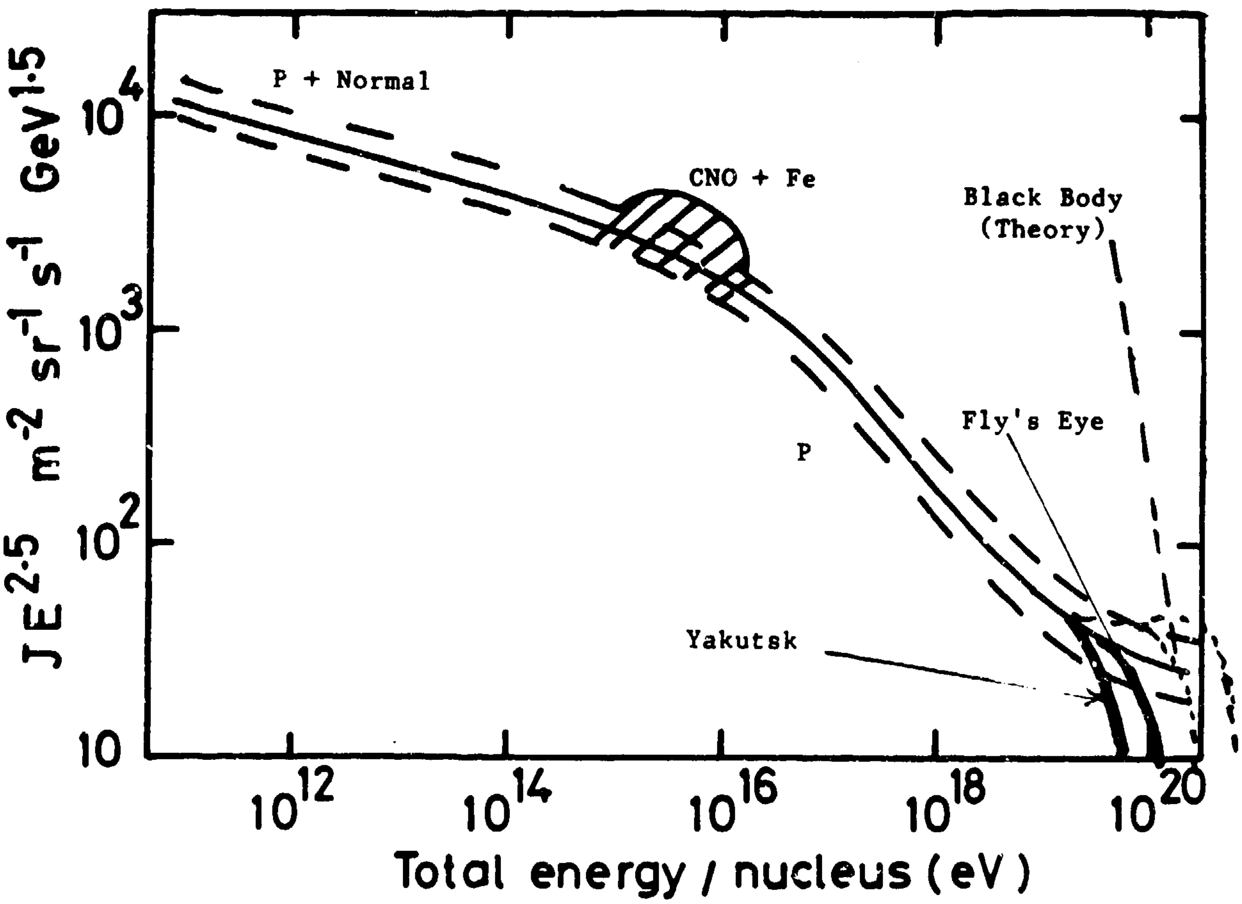

Fig. 1. The differential energy spectrum of cosmic rays above 10^{11} eV (total energy). The solid curve is an eyeball fit through the data surveyed in /1/. The dashed lines are ±20% from the solid line. It seems certain that the true spectrum lies within these bounds except in the shaded region near 10^{15} eV where matters may be more complicated and near 10^{20} eV where statistical and energy calibration uncertainties may mean that the ±20% bounds are optimistic.

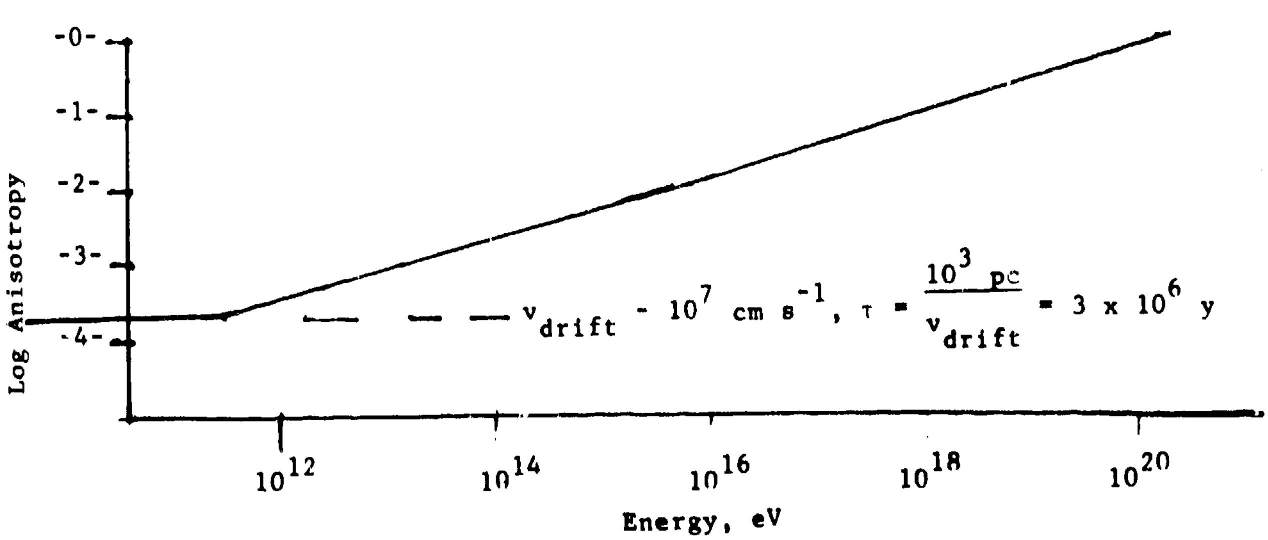

Figure 2

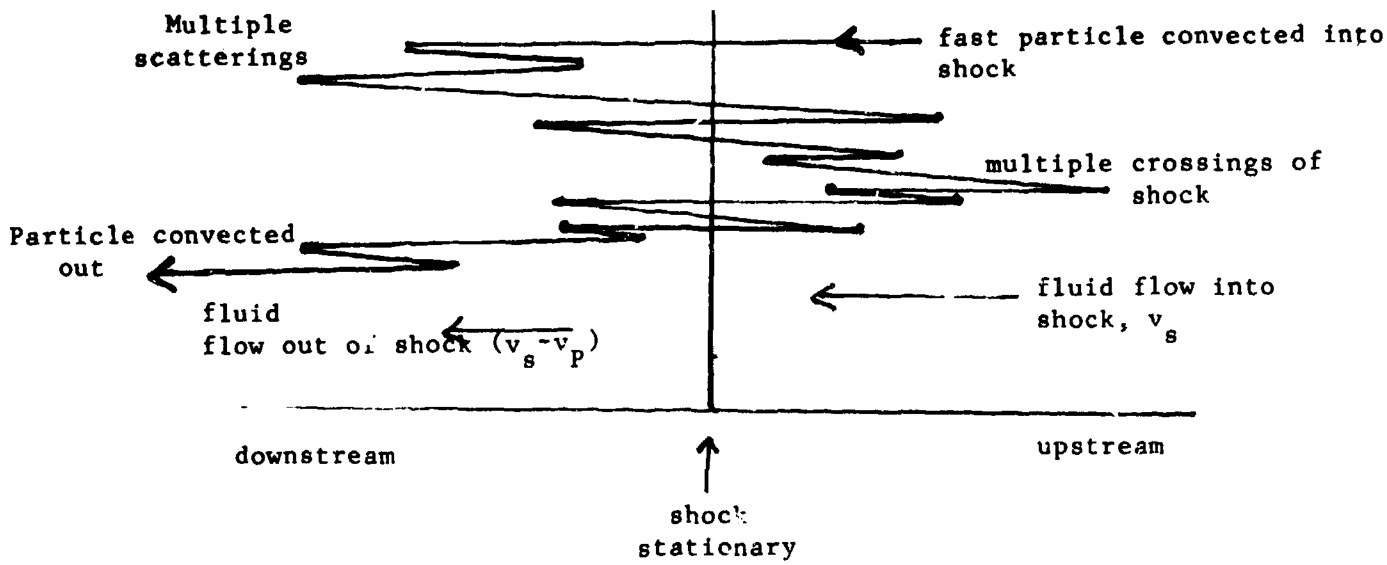
Multiple scatterings
fast particle convected into shock
multiple crossings of shock
Particle convected out
fluid flow out of shock $(v_s - v_p)$
fluid flow into shock, v_s
downstream
upstream
shock stationary

Figure 3

SNI Envelope Shock

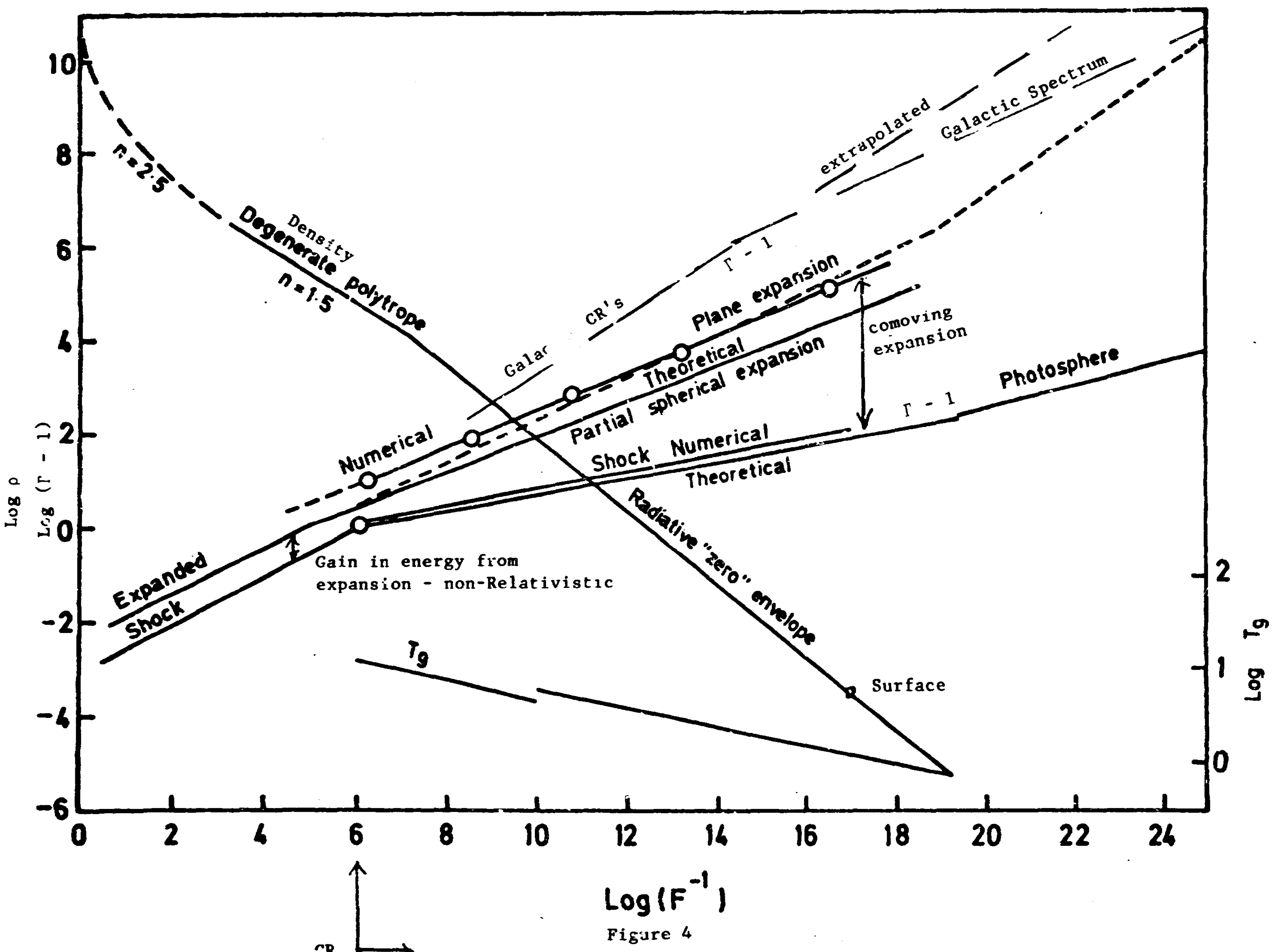

Figure 4

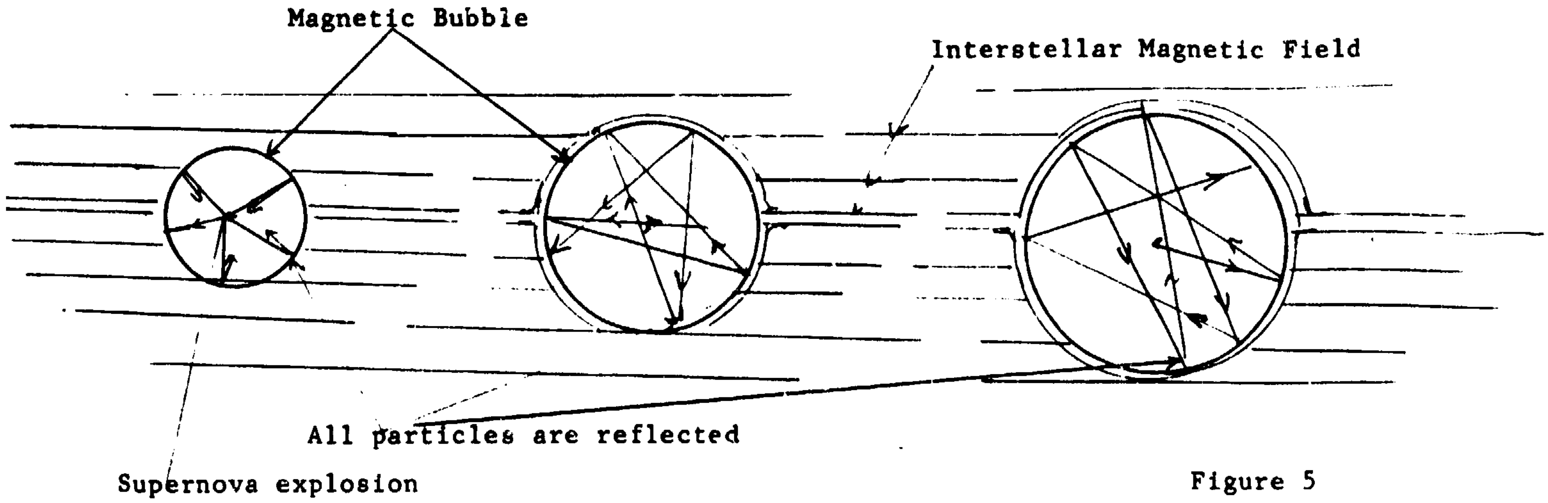

Figure 5

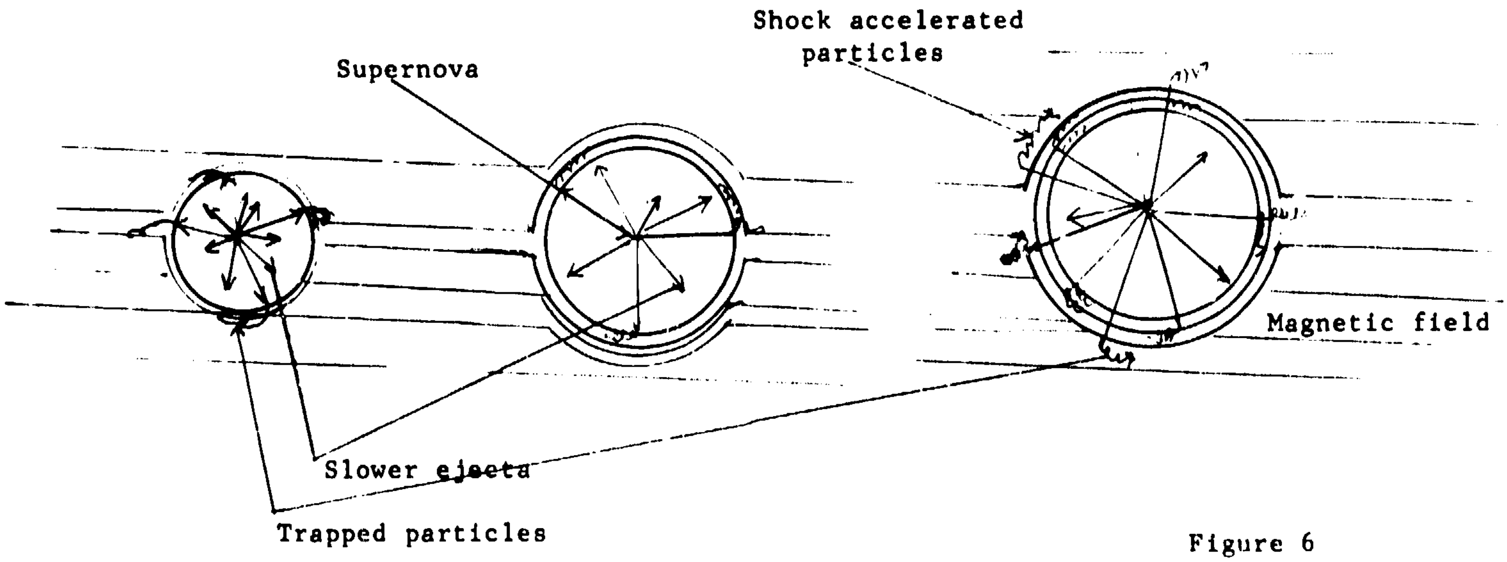

Figure 6

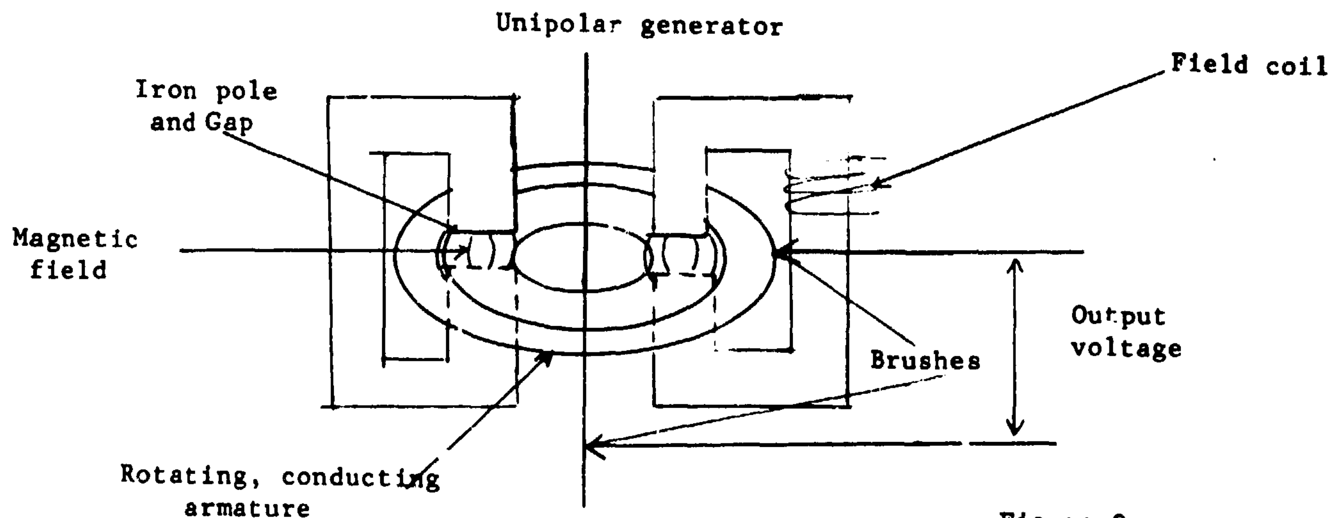

Figure 9

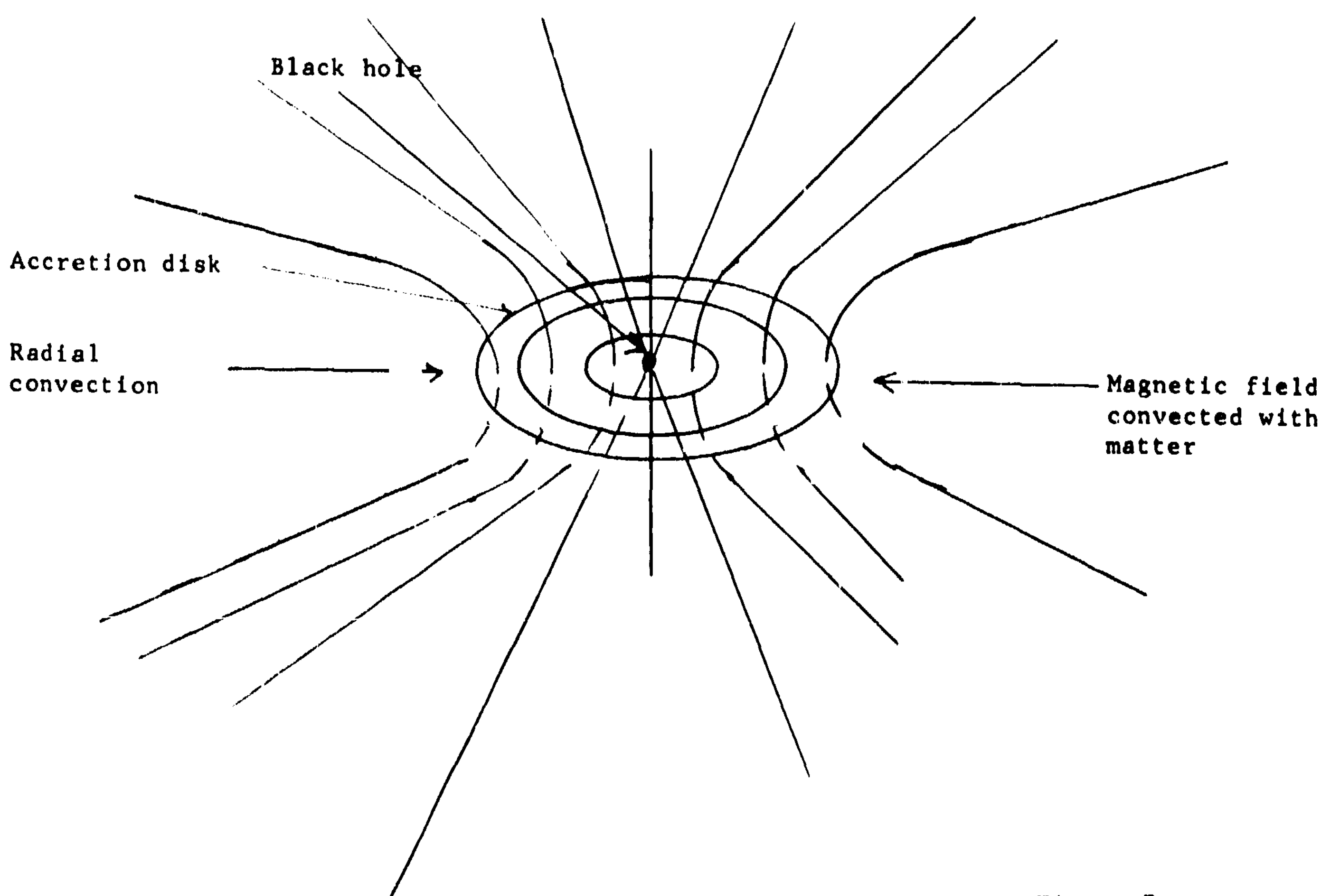

Figure 7

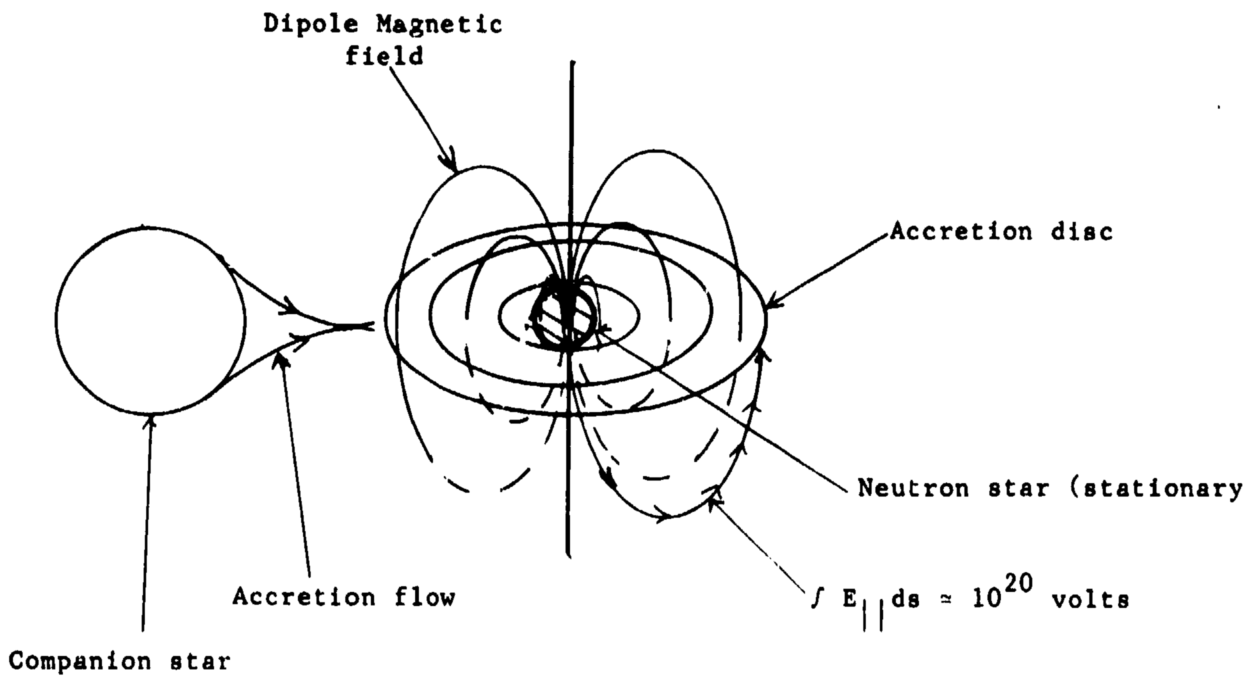
Dipole Magnetic field
Accretion disc
Neutron star (stationary)
$\int E_{||} ds \simeq 10^{20}$ volts
Accretion flow
Companion star

Figure 8